

Are Quantity-Distances Narrowing in?

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Abstract

Quantity-Distance (QD) is an established method used among other things for safety related to ammunition storage. The beauty of the QD-method is obvious - the simplicity - a simple solution to a complicated problem.

As often is the case, the simple solution may be too simple for some applications. This makes a need to question the QD-method - if, when and how to use it.

QD methods are generally appreciated by authorities who have to apply it and they consider it easy to understand (Acceptable - Not acceptable and nothing in between). Technical people who are involved in the ammunition safety process are well aware of the deficiencies associated with it. These deficiencies have led to alternate ways to be used in safety regulations e.g. methods based upon risk analysis.

Increased costs for land and military operational requirements make it necessary both to apply alternate methods to ensure adequate safety and to question the criteria behind the QD:s and how they are used for different situations.

The paper describes the background to and the development of some current regulations for the storage of ammunition. Comparisons are made of different criteria used and how these criteria influence on QD:s and Field Distances for the Military Operational Theater.

The paper gives special emphasis on work done within the NATO AC/326 Operational Safety Group and efforts made to reduce Field Distances in the interest of Operational Readiness.

Background

Quantity-Distance (QD) tables give an easy to use method for limiting consequences from accidental explosions. The method is well established and widely used. One area is for safety storage of ammunition.

The simple solution may be too simple for some applications. This also goes for the QD-method. Increasing costs for land and increased military operational requirements make it necessary to question the QD:s for different applications and the criteria behind them and what QD:s to chose when there is a choice - as well as to identify situations where existing QD:s do not offer an adequate tool for safety handling and suggest a tool that does. For ammunition storage safety problems this can lead to alternate QD:s or the use of methods based upon risk analysis.

A starting point for the discussion of QD:s could be to study some existing QD:s and the rational for them and to what extent and why they differ e.g. different origin, different purpose, different criteria or just different interpretations of data.

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A NATO perspective as well as the increasing international co-operations lead to an increased demand to unify regulations. These demands are the reason for NATO-and PFP-countries to develop and adopt AASTP-1 and AASTP-5 for ammunition storage /1/, /2/.

Quantity-Distance History

The history of QD goes far back, see e.g. /3/, /4/, /5/, /6/. Reference /3/ quotes /7/:

"Act for preventing the Mischiefs which may happen by keeping too great Quantities of gunpowder in or near the Cities of London and Westminster, or the Suburbs thereof".

In this act is stated:

"Whereas great Quantities of Gunpowder are frequently Lodged and Kept in Warehouses and other Places in and about the Cities of London and Westminster, and the suburbs thereof, to the apparent Danger, if not utter Ruin and Destruction of several Publick Offices, and of the Lives and Fortunes of many Thousands of his Majesties Subjects".

To prevent this from happening the Act made clear:

"That from and after the first day of August, 1719 it shall not be Lawful for any Person or Persons to have or keep more than Six hundred Pounds of Gunpowder, each Hundred containing Fivescore Pounds Net Weight, at any time, in any Storehouse, Warehouse, or other Place, within the Cities of London and Westminster, or either of them, or within the Suburbs thereof, or within Three Miles of the Tower of London, or within Three Miles of His Majesties Palace at St. James's or within Two Miles of any Magazine now Erected for Keeping Gunpowder, belonging to His Majestie, His Heirs or Successors, for the Use of the Publick".

Dealers in gunpowder quickly found ways to circumvent the Act by dividing their stores to smaller, individual, magazines leading to a new Act with the lower total quantity of 200 lb. and explicitly excluding dividing up the store into multiple units.

However, it seemed easier to pass Acts like this than to enforce them.

Regulations normally were the result of accidents that had occurred and increased the pressure upon authorities to act.

Various refinements were made through the years and a new landmark was the Explosives Act of 1875.

The Explosives Act of 1875 introduced specific explosives quantity/distance tables where distances to be kept clear from public railways and highways, dwellings with or without the consent of owner were given (in Feet) and from Palace or House of Residence of Her Majesty (in Miles), see Table 1.

AMOUNT OF EXPLOSIVE <i>Pounds</i>			DWELLING, WITH CONSENT	DWELLING, WITHOUT CONSENT	PALACE OR HOUSE OF RESIDENCE
	PUBLIC RAILWAY <i>Feet</i>	PUBLIC HIGHWAY <i>Feet</i>	OF OWNER <i>Feet</i>	OF OWNER <i>Feet</i>	OF HER MAJESTY <i>Miles</i>
500			150	300	2
1000		225	225	450	2
5000	675	312	390	960	2 1/4
10,000	795	330	525	1,575	2 3/4
15,000	900	345	645	2,070	3 1/4
20,000	990	360	750	2,550	3 1/2
50,000	1,575	450	1,425	5,550	6
100,000	2,550	600	2,550	10,500	10

Table 1. Distances to be kept clear from different objects at different amounts of explosives. From /3/.

When the state of Massachusetts established an explosives distance vs. weight table in 1904 reference was made to prior British work.

Colonel Dunn, Chief Inspector of the Bureau of Explosives, representing the American Railway Association showed the needs for drastic changes in how to place storages with explosives. He convened a conference of explosive manufacturers to discuss safe storage and leading to the establishment of the American Table of Distances in 1910 based upon a study of the effects of explosions on their surroundings. 117 explosions were thoroughly studied 92 of which with damage other than broken glass. 67 of these structures of light frame construction while the remainder were of substantial brick or masonry. The accidents ranged from very small amounts to millions of pounds. The Institute of Makers of Explosives adopted the tables giving the minimum permissible distance allowed for inhabited buildings for quantities of explosive up to 5000 tons.

Distances from railways were set to 60% of the inhabited building distances. Reasons for this were a lesser height and a smaller area of railroad car exposed to concussion and the greater strength of railroad cars compared with buildings. Also buildings are stationary and continually exposed to risks whereas trains' presence is temporary.

Highways were added to the tables in 1914. Incidentally, the distances were the same as for railroads.

The source of explosion was premised to be behind a barricade. For barricaded situations half of the real distances was used when comparing to non-barricaded situations, see Figure 1.

Neither explanation nor justification was given for this assumption. Also in the current version of ATD, /8/, a distinction between barricaded and non barricaded explosives is used.

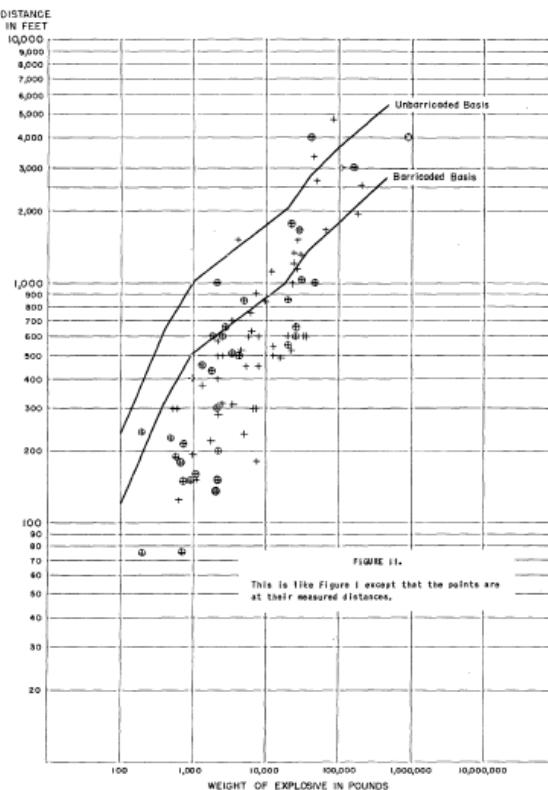
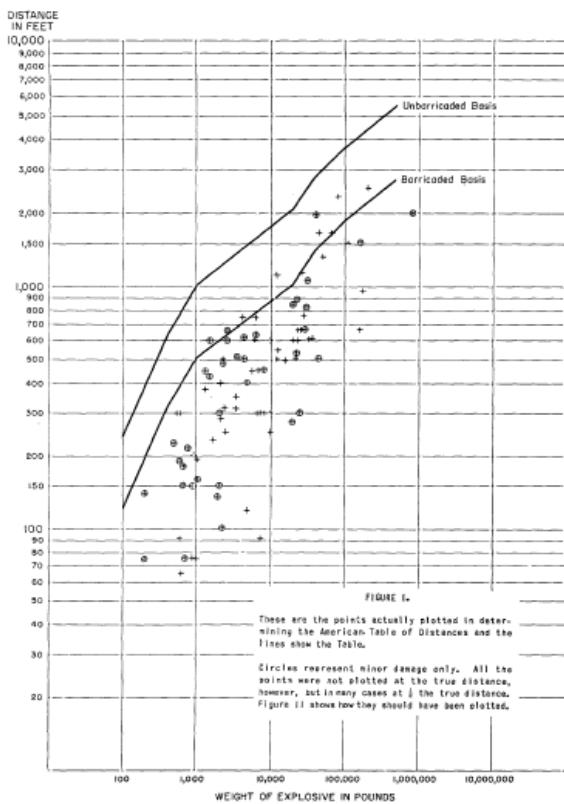


Figure 1. The American Table of Distances as used with barrier distances reduced by half (left) and with actual distances (right). It can be seen that the reduction by half for barricades is unconservative.

Obviously the reduced distances used in Figure 1 give a false impression of required distances.

It was made explicit that the table "is not intended to apply to bombs, projectiles, or other heavily encased explosives".

The table was reviewed in 1919 and again in 1939 considering new data accumulated by those years.

Additional work by Assheton, /9/, was based upon the same material as the original ATD and, in addition, eighteen more explosive accidents.

Assheton noted that the distances fitted well to the third root of explosive weight multiplied by a constant though this was not exploited until later, /4/. The scaled distance ($R/Q^{1/3}$ where R is the distance and Q the net explosive quantity) in turn can be associated with a certain blast-overpressure level.

As no attempt was made when making the ATD to classify the degree of damage - broken glass and structural damage were the only two categories, the distances do not say anything about the maximum distance for certain damage. The distance reported will always be shorter than the possible maximum.

While the ATD was intended for civilian use also the need for military regulations for ammunition storage was recognized. The major accident in Lake Denmark in 1926 led to the US Government adopted the ATD in 1928 to be used by the military services.

In 1945, Colonel C. S. Robinson at Ordnance Department, of the US Army looked more in detail into the ATD and made serious criticism of it, /6/.

He found, that the ATD seemed to over-estimate consequences at small distances and underestimate consequences at larger distances and did not at all cover ranges for very large quantities of explosives.

Also, developments since the tables were made had led to new, more energetic and powerful, explosives making distances based on older material non-conservative.

Col. Robinson also questioned the rationale for blast reduction from barriers outside of a range of a couple of times of the barriers height.

According to Col. Robinson the ATD was in systematic error giving non-conservative distances.

Additional work from Assheton /10/ has recently been re-analyzed, /11/. By a detailed study of injuries and lethality from explosions in Assheton's work a relationship between the probability of no injury, minor injury, major injury and fatality vs. distance showed that minor injuries were almost independent of the distance, within the range studied, while the probability of major injuries and fatalities – as expected – increased with decreasing distance (K-factor).

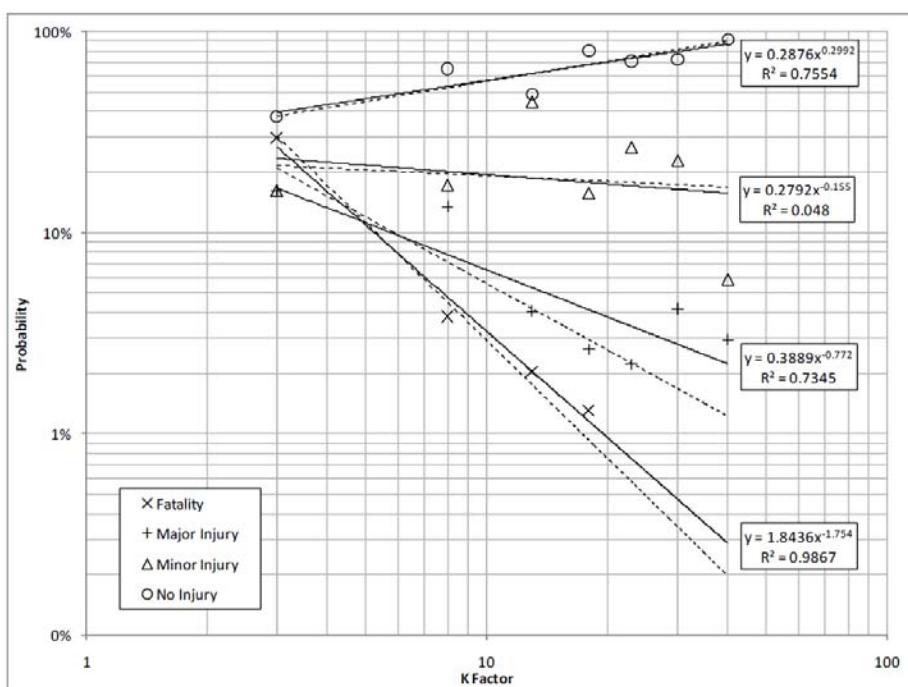


Figure 2. Probability of injury and fatality vs. distance (K-factor) (from /11/).

NATO

In 1971, NATO AC/258 adopted the United Nations classification system for use in the transport of explosives for the storage of military ammunition and explosives, /12/. A concept for storage of ammunition was gradually developed and the resulting Manual, Safety Principles for the Storage of Military Ammunition and Explosives, AASTP-1, Edition 1 among other things applied Quantity-Distances. This was done in a similar way compared to US and UK regulations.

IBD could be calculated from $d(m)=22,2*Q^{1/3}$ with Q, the net explosive mass, in kg.

The criteria used were for blast an overpressure of 5 kPa and for fragment a density of one lethal fragment per 56 m^2 . A fragment was considered lethal if the kinetic energy was above 79 Joule.

In 1981, a part IV for operational situations was included in AASTP-1. Later, within NATO AC/326 a new Manual, NATO Guidelines for the Storage, Maintenance and Transport of Ammunition on Deployed Missions or Operations, AASTP-5, /2/, has been developed to cater for operational situations where AASTP-1 can not be applied and higher risks and more severe consequences must be accepted due to operational requirements.

In developing acceptable Field Distances for operational situations instead of the QD:s in AASTP-1 the difficulty was noted with the blast criteria in terms of building damage and the debris criteria expressed as a certain density of lethal fragments.

The question is if the criteria really are the most adequate to use?

Criteria

1. Blast

The QD:s according to the above are from blast and fragments. For blast, typically, a pressure level of 5 kPa is used for IBD. For people in the open this pressure must be considered to be low – even the chance of eardrum rupture is small.

For people in buildings the chance of damage, however, might be higher, in particular due to injuries from breaking glass windows. On the other hand even significant building damage does not lead to a corresponding high fatality rate. Figure 3 shows fatality rate vs. structural damage according to /13/, illustrating this effect.

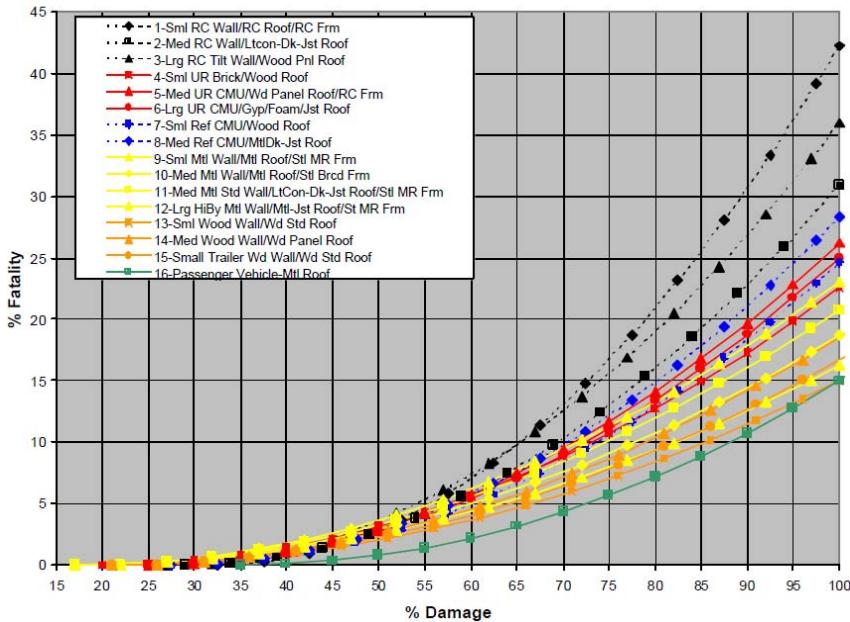


Figure 3. Fatality vs. Structural Damage according to /13/.

The blast criteria give a negligible risk for lethality at IBD compared to the criteria for fragments and debris for people in the open.

2. Fragments

The background to the energy of a lethal fragment can be found in /5/. The number comes from Danish experiments using pine boards and live horses as targets for missiles and quoted in a text-book intended for cadets of the U.S. Military Academy, /14/. It seems to be based originally upon a Germany Army doctrine /15/.

Studies referenced by Peter Kummer /17/ show how the lethality is very much depending on not only the kinetic energy of the fragment but also the point of impact. For a fragment hitting directly on the head a much smaller energy is lethal than for a fragment hitting in the limbs, where much higher energies are needed for serious consequences.

Figure 4 is an illustration to this.

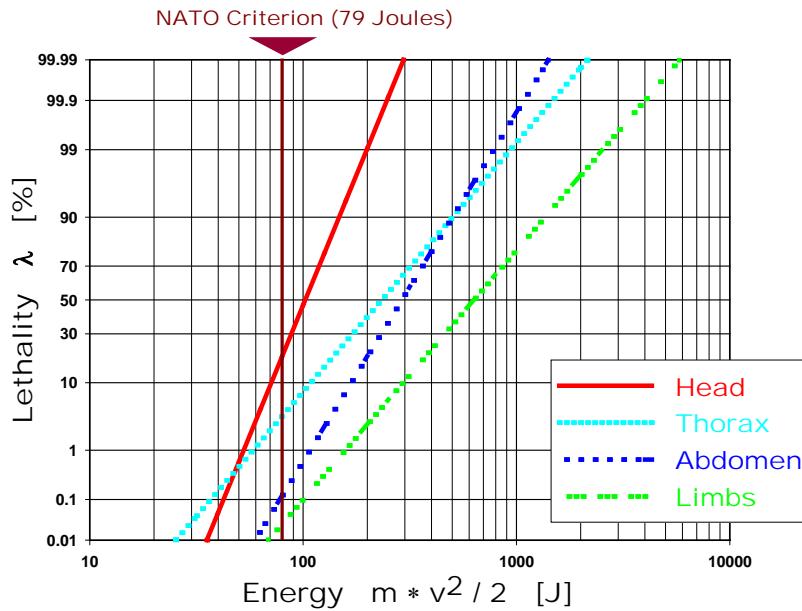


Figure 4. Lethality vs. fragment energy for different parts of the human body. From /16/ and /17/.

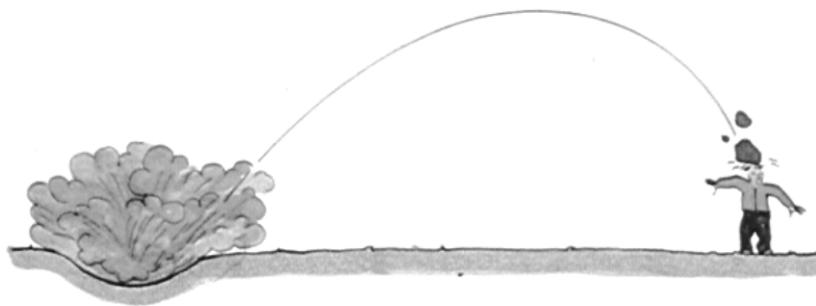


Figure 5. Crater debris with trajectories with a vertical component.

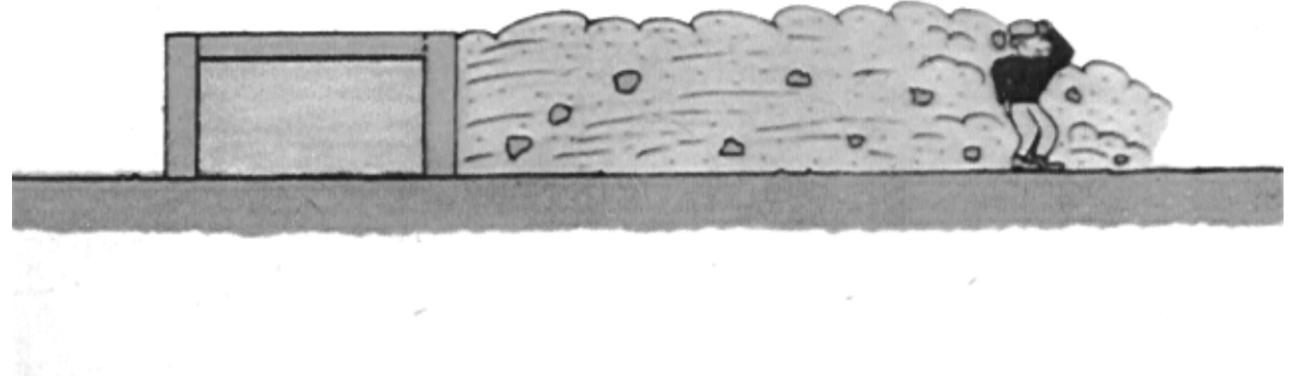


Figure 6. Horizontal debris, e.g. from disintegrating walls.

One could also question the use of a horizontal area. Figures 5 and 6 show two cases with debris. Only in the first case can a horizontal surface be considered as adequate for a study of debris density.

It could be pointed out, that a barrier may be very effective in stopping horizontally directed fragments as in Figure 6, but to stop fragments with close to vertical trajectories often unrealistically high barriers are needed or overhead protection must be used.

In addition, the size of the horizontal area, 56 m^2 , can be questioned as being arbitrary. According to /5/ it has its origin from WW II studies in UK and refers to the (vertical) front face of an ordinary dwelling.

The size of a person as well varies and, conclusively, the chance of being hit by a fragment, see Figure 7.

In conclusion, the debris energy, the lethality and the area density could all be questioned. Still, though, these values have a long history and have gained much support worldwide for a long time.

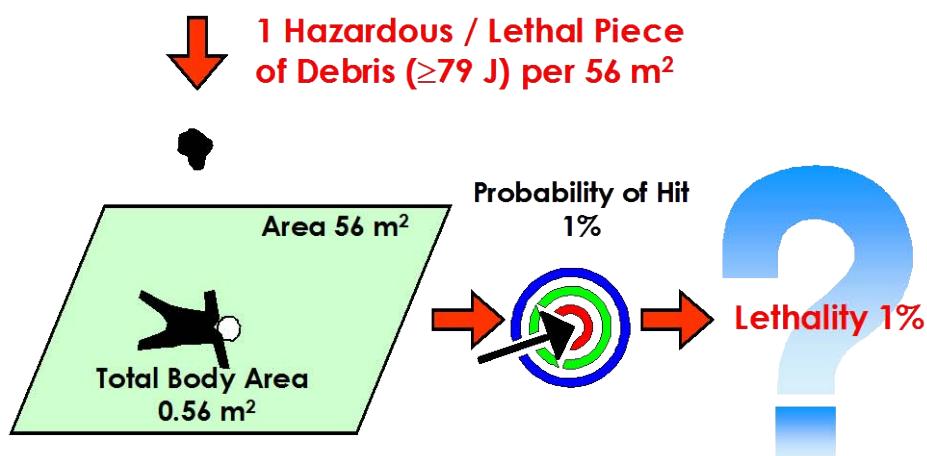


Figure 7. Lethality from fragments, Principle according to /17/.

AASTP-5

“AASTP-5 applies when AASTP-1 and AASTP-2, and rules described in international and national regulations, cannot be applied” (AASTP-5 Para 1.1c). It “establishes minimum requirements that are based on reducing the maximum credible event (MCE) to no greater than 4000 kg net explosive quantity (NEQ), to avoid/reduce loss of personnel and material, minimize the effects of unintended detonations/reactions during storage, transportation and handling or as a result of enemy action”.

Conclusively there are differences - and should be differences - compared to AASTP-1.

From the above it should be obvious that the criteria used for QD:s could not readily be used for AASTP-5. New criteria had to be developed.

AASTP-5 gives Field Distances (FD) which could well be compared with QD:s but should not be mistaken for QD:s. Field Distances are distances applied from a PES to other PES or ES located within a compound, that is an area that incorporates functions, facilities, and operations necessary for the accomplishment of a mission.

The FD:s are given for different types of PES and ES.

The PES are divided into:

Hardened e.g. armoured combat vehicles and ISO containers/sites protected by 1m thick concertainer and with 0.6 m over head sand/gravel.

Semi-hardened e.g. light armoured combat vehicles, with 0.6 m sand/gravel overhead and armour plated side protected ISO/containers/sites and

Light e.g. containers, wooden, concrete and brick structures, non armoured vehicles and open stacks.

The ES in addition to Hardened, Semi-hardened and Light are given as

Open e.g. mission related personnel and

Unprotected people outside compound.

The background of the Field-Distances in AASTP-5 can be found in /18/.

AASTP-5 Field Distances are based upon HD 1.1. Sensitivity Groups 1-5 are all treated the same way in AASTP-5. These limitations are introduced to facilitate the use of AASTP-5 by avoiding many tables but of course means that a degree of conservatism is introduced for the lesser Sensitivity Groups and for other Hazard Division material.

A. Distance between barricaded PES

The distances between different PES to PES categories with a barricade in between are A1 for Hardened, A2 for Semi-hardened and A3 for Light structures, respectively.

A minimum distance of 4 m is foreseen for all cases A1-A3 assuming a 2 m barrier that should be adequate to protect from initiation from one PES to another for Q up to 1000 kg corresponding to $0.4*Q^{1/3}$. For Q in the interval 2000-4000 kg the FD is $0.6*Q^{1/3}$.

AASTP-1 gives the distance 7 m for 500 kg and 8 m for 1000kg ($0.8*Q^{1/3}$). A comparison with distances in AASTP-1 is given in Table 2.

NEQ (kg)	A1,A2,A3	AASTP-1
	FD(m)	QD(m)
50	4	N/A*
100	4	N/A*
500	4	6
1000	4	8
2000	8	10
4000	10	13

*Table 2 A1-A3 FD:s compared with AASTP-1. * AASTP-1 handles amounts from 500 kg and up.*

B. Distance between PES and barricaded ES

The barricade is considered effective if in between the PES or ES - not necessarily closed to either. The ES is assumed protected from fragments by the barrier and therefore the blast pressure is the key factor for the FD.

NEQ (kg)	B1	AASTP-1 Part IV*	B2	B3	B4	B5
	FD(m)	QD(m)	FD(m)	FD(m)	FD(m)	FD(m)
50	15	N/A	22	33	100(33)	100
100	19	N/A	28	46	100(46)	100
500	32	64	48	103	155	155
1000	40	80	60	130	235	235
2000	50	101	76	164	320	320
4000	64	127	95	206	400	400

Table 3. FD B1-B5 compared with AASTP-1. *For Protected personnel.

A pressure of 65 kPa was chosen corresponding to a distance of $4*Q^{1/3}$ free field. However, the pressure within an ES could vary with orientation as well as design and be both higher and lower than this value. At this pressure level the chance of ear-drum rupture is about 20 %.

B3 is based upon $4.6*Q^{1/2}$ for amounts less than 500 kg and $13*Q^{1/3}$ for larger Q for light structures that can resist high trajectory fragments at terminal velocity.

For other light structures, B4 FD according to the formula $100+5.5*(Q-400)^{1/2}$ with a minimum distance set to 100 m should be used.

B4 values also open for the case where the PES is designed (and approved nationally) to resist fragments (numbers within brackets).

The square root (instead of cube root) is based upon the finding that for smaller charges the damage is depending on pressure and duration why a cube root scaling could under predict damage. It should also be noted that the distances due to blast are larger than for people in the open (based on blast) due to the fact that a light structure, like a tent, could well cause serious damage to personnel when subjected to blast.

The distances to people outside the camp should be the same as AASTP-1 values. The reason for this is that this distance may apply to third party people not directly involved in or benefiting from the activities.

From a political/ethical point of view it is reasonable that effects should not exceed the levels that people in the home country may be exposed to.

C Distance between unbarricaded PES

For unbarricaded PES to hardened PES the situation is similar to the case with barricades and, conclusively, the distances for C1 and A1 are identical.

For semi-hardened PES the distance is set to $2.4*Q^{1/3}$ which is in agreement with /19/ for IMD and presuming that semi-hardened structures can prevent low trajectory fragments to penetrate and cause initiation of explosives.

NEQ (kg)	C1	C2	C3
	FD(m)	FD(m)	FD(m)
50	4	9	18
100	4	11	22
500	4	19	38
1000	4	24	48
2000	8	30	60
4000	10	38	76

Table 4. FD C1-C3.

D Distance between unbarricaded PES and ES

As Hardened structures are supposed to withstand high velocity low trajectory fragments, blast is the critical factor. Conclusively, D1 values are identical to B1 values, based upon $4*Q^{1/3}$.

For semi-hardened PES the distance is set to $8*Q^{1/3}$. This distance is the same as AASTP-1 Part IV for Protected Personnel, see Table 2.

For light structures, personnel in the open and people outside the compound it was decided to have the same distances as the danger comes from fragments.

NEQ	D1	D2	D3,D4,D5
	FD(m)	FD(m)	FD(m)
50	15	29	212
100	19	37	294
500	32	64	400
1000	40	80	400
2000	50	101	400
4000	64	127	400

Table 5. FD D1-D5.

A comparison of QD from AASTP-1 with FD from AASTP-5 clearly points out:

- The criteria used for QD:s could not readily be used for AASTP-5,
- AASTP-5 covers also small charges which AASTP-1 does not,
- AASTP-5 is limited to 4000 kg simultaneous detonation which requires barricades between PES or hardened structures for the subdivision for larger amounts into maximum 4000 kg
- Barricades drastically reduce FD. The use of barricades in the interest of increased safety is rewarded.

Conclusions

The hazards from an explosion in a munition storage are mostly from blast, fragments and debris. The pure blast effects are for smaller charges concentrated to the area close to the charge while fragments and debris can travel large distances.

The criteria used for QD could not be used directly for Field Distances in AASTP-5.

To reduce Field Distances higher blast levels must be accepted and measures taken to reduce effects from fragments and debris. In accordance with that, AASTP-5 strongly advocates the use of properly designed barriers.

Risk analysis methods are introduced as an option in AASTP-5.

Acknowledgement

AASTP-5 – like AASTP-4 – is the result of qualified discussions and cooperation by experts from different nations. The author is very appreciative for having had the opportunity to share experiences and to make progress together with these experts.

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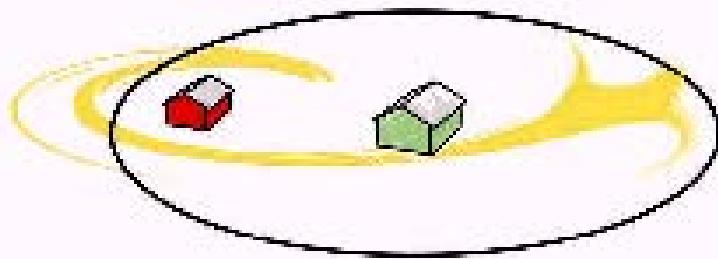
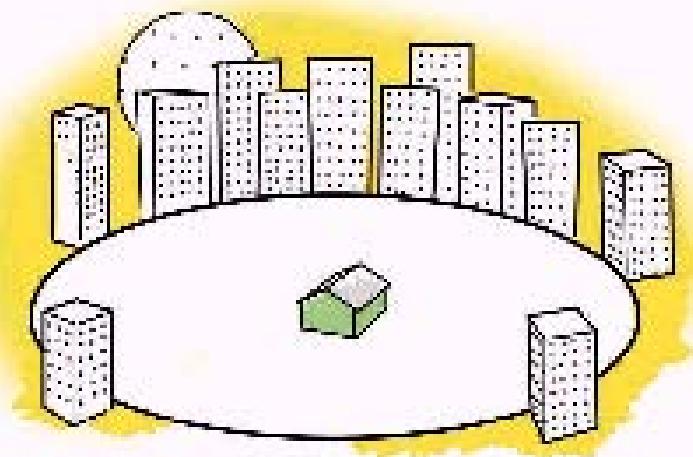
DDESB Seminar, Portland, Oregon, July 13th, 2010

"SAFE"

UNSAFE



Q-D



"Whereas great Quantities of Gunpowder are frequently Lodged and Kept in Warehouses and other Places in and about the Cities of London and Westminster, and the suburbs thereof, to the apparent Danger, if not utter Ruin and Destruction of several Publick Offices, and of the Lives and Fortunes of many Thousands of his Majesties Subjects"

"Act for preventing the Mischiefs which may happen by keeping too great Quantities of gunpowder in or near the Cities of London and Westminster, or the Suburbs thereof (1719)"

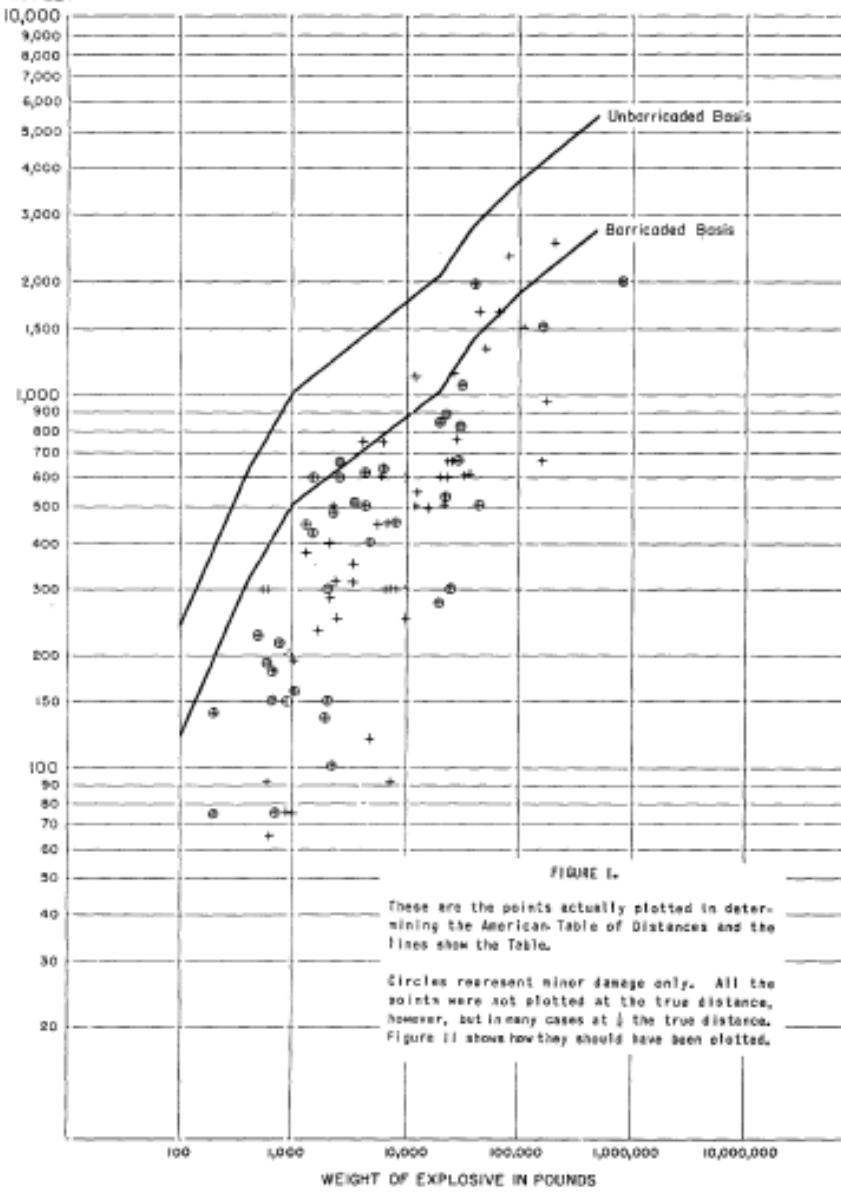
"That from and after the first day of August, 1719 it shall not be Lawful for any Person or Persons to have or keep more than Six hundred Pounds of Gunpowder, each Hundred containing Fivescore Pounds Net Weight, at any time, in any Storehouse, Warehouse, or other Place, within the Cities of London and Westminster, or either of them, or within the Suburbs thereof, or within Three Miles of the Tower of London, or within Three Miles of His Majesties Palace at St. James's or within Two Miles of any Magazine now Erected for Keeping Gunpowder, belonging to His Majestie, His Heirs or Successors, for the Use of the Publick."

AMOUNT OF <i>EXPLOSIVE</i> <i>Pounds</i>	PUBLIC RAILWAY <i>Feet</i>	PUBLIC HIGHWAY <i>Feet</i>
500		
1000		225
5000	675	312
10,000	795	330
15,000	900	345
20,000	990	360
50,000	1,575	450
100,000	2,550	600

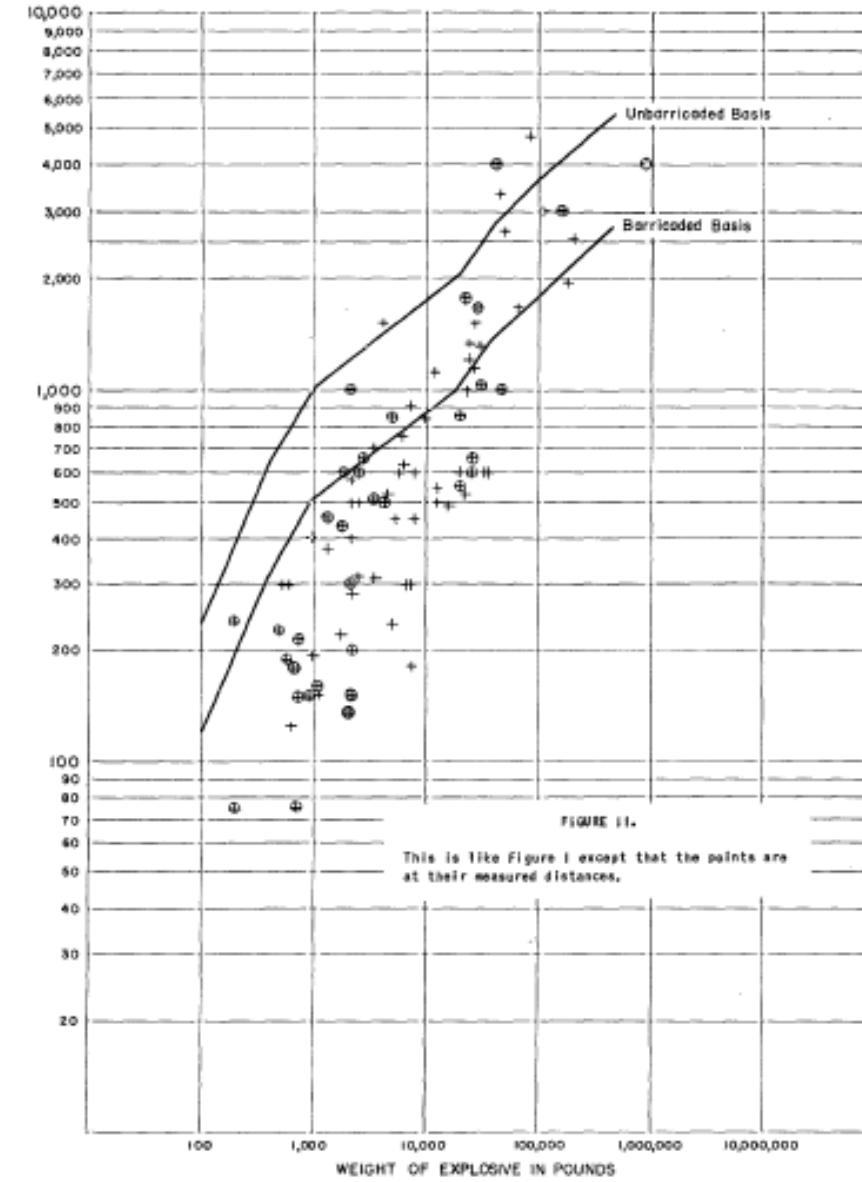
Explosive Act, 1875



DISTANCE
IN FEET



DISTANCE
IN FEET



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2010-07-13



CRITERIA

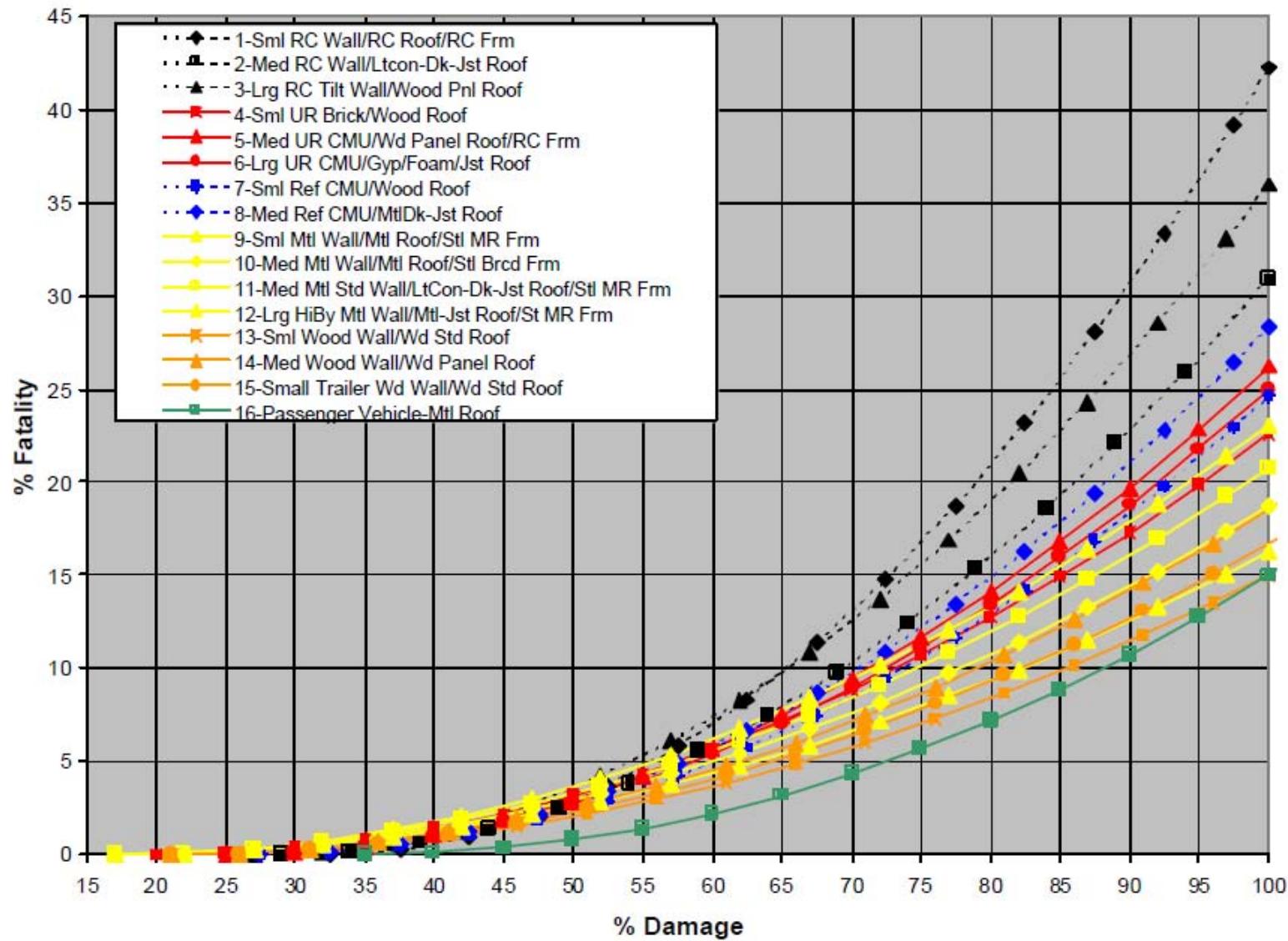
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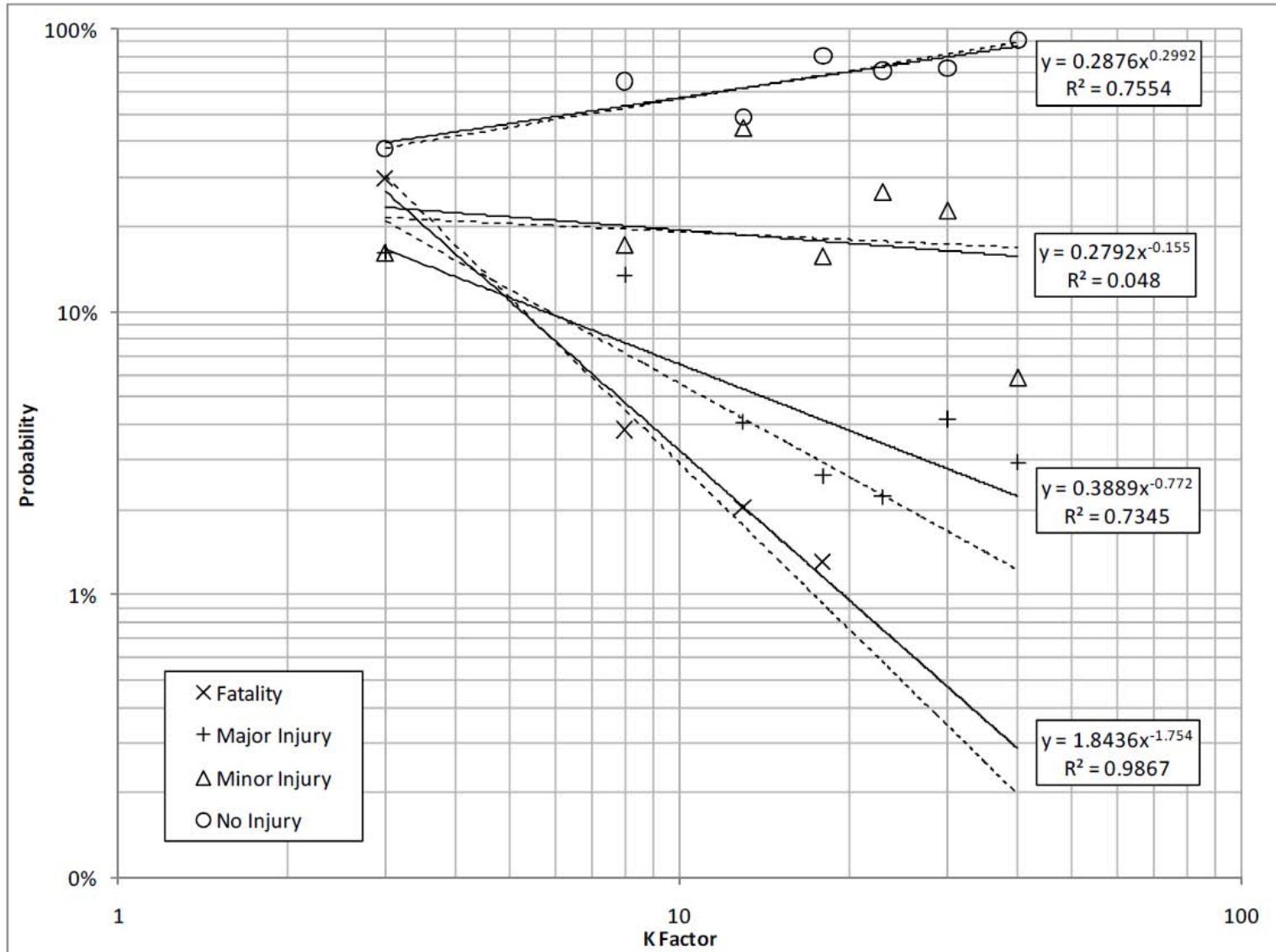
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TABLE C2.T3. GENERAL BLAST EFFECTS ON PERSONNEL—EARDRUM RUPTURE

EFFECT	Incident Pressure (psi) [kPa]	K-FACTOR (ft/lb ^{1/3}) Km-FACTOR [m/kg ^{1/3}]	PROBABILITY (%)
Eardrum Rupture	3.0	20.0	1
	20.7	7.87	
	3.6	17.9	2
	24.5	7.08	
	4.9	14.6	5
	33.8	5.78	
	6.6	12.2	10
	45.7	4.84	
	9.0	10.3	20
	62.1	4.10	
	15.0	8.0	50
	103.6	3.16	
	74.4	3.9	99
	513.0	1.55	



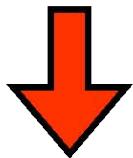




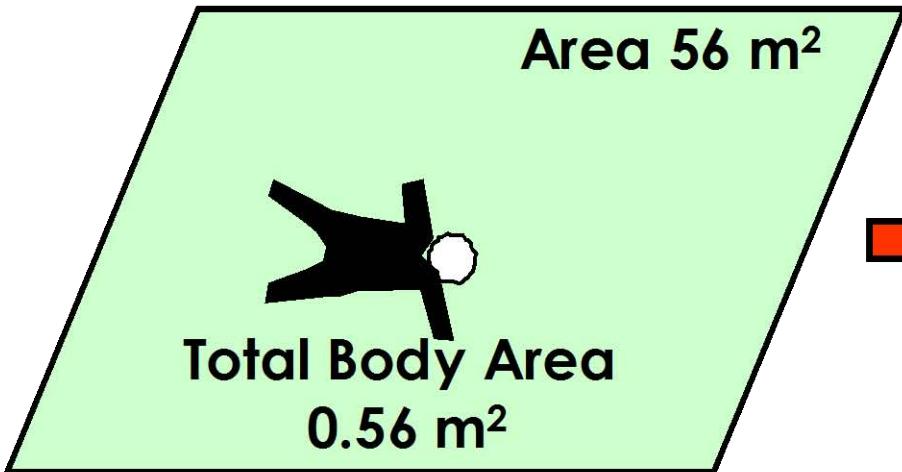
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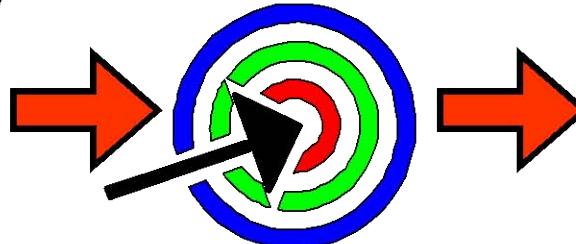


**1 Hazardous / Lethal Piece
of Debris (≥ 79 J) per 56 m²**

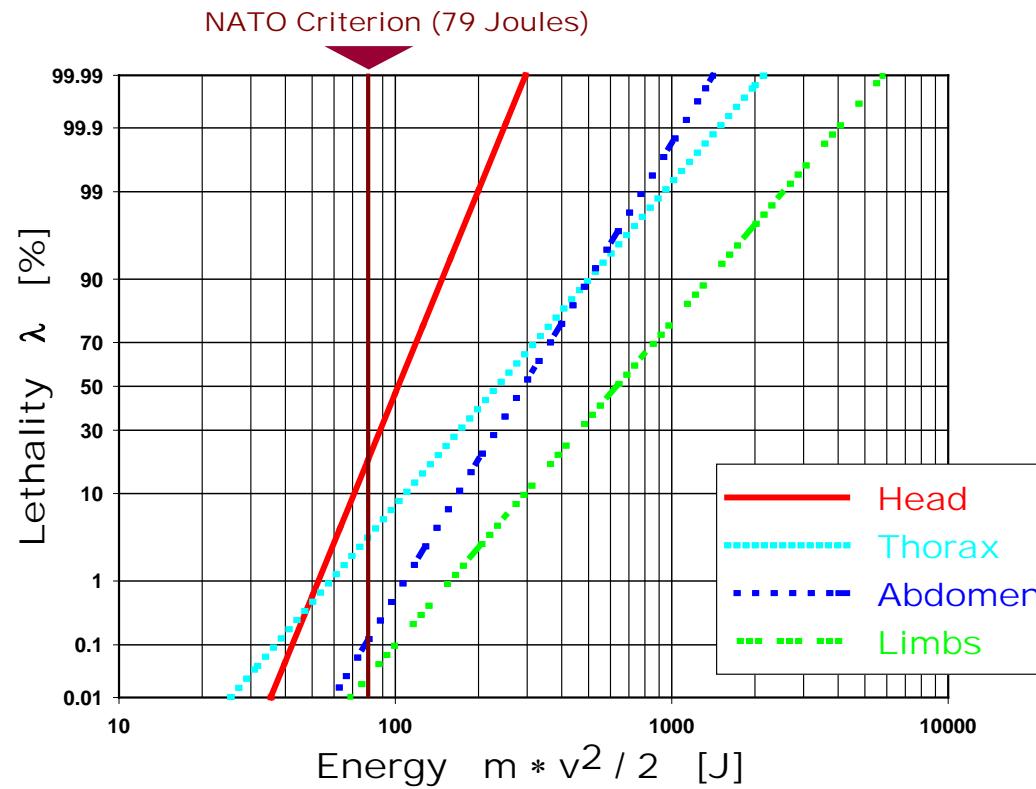


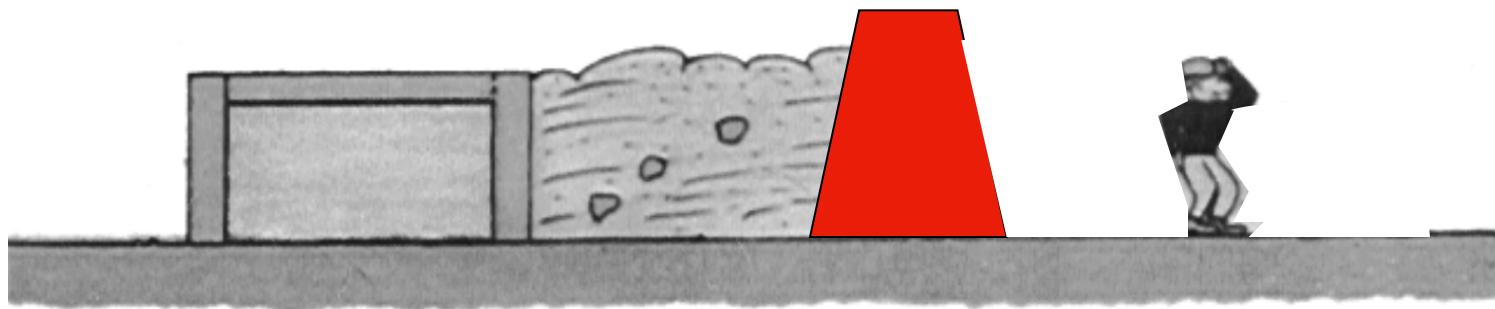
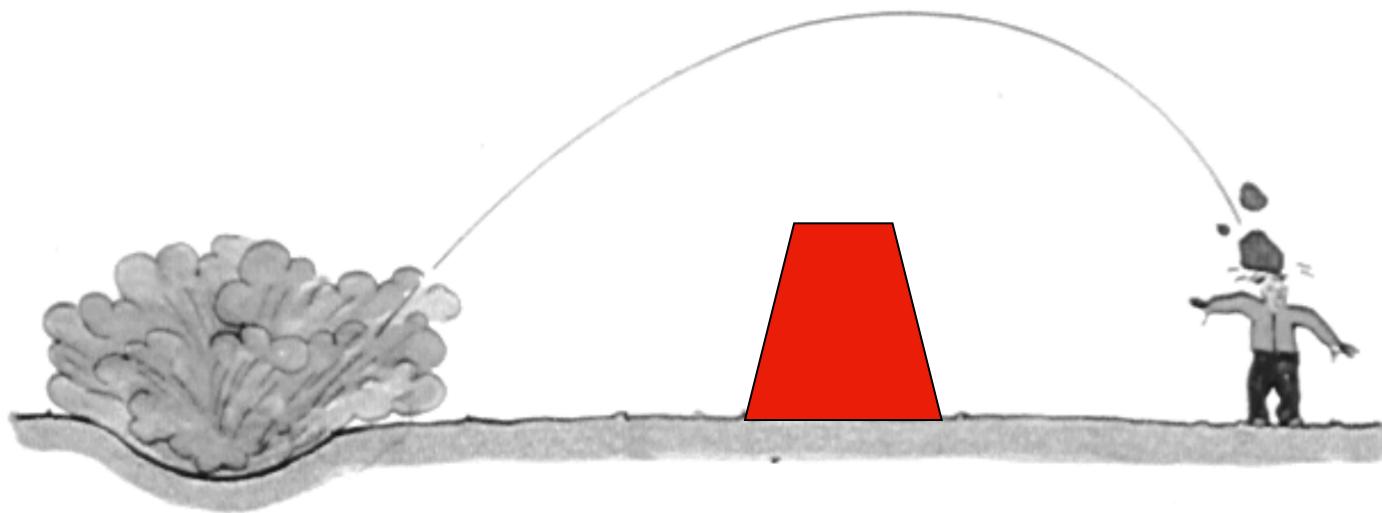
Probability of Hit

1%



Lethality 1%





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AASTP-5

- **Hardened** e.g. armoured combat vehicles and ISO containers/sites protected by 1m thick concertainer and with 0.6 m over head sand/gravel.



- **Semi-hardened** e.g. light armoured combat vehicles, with 0.6 m sand/gravel overhead and armour plated side protected ISO/containers/sites and



- **Light** e.g. containers, wooden, concrete and brick structures, non armoured vehicles and open stacks.

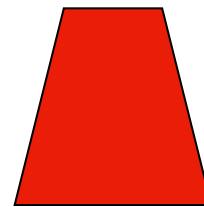


- **Open** e.g. mission related personnel and
- **Unprotected people outside compound.**

PES to PES



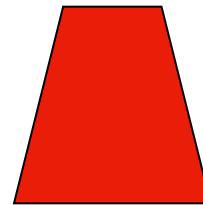
w/o



PES to ES

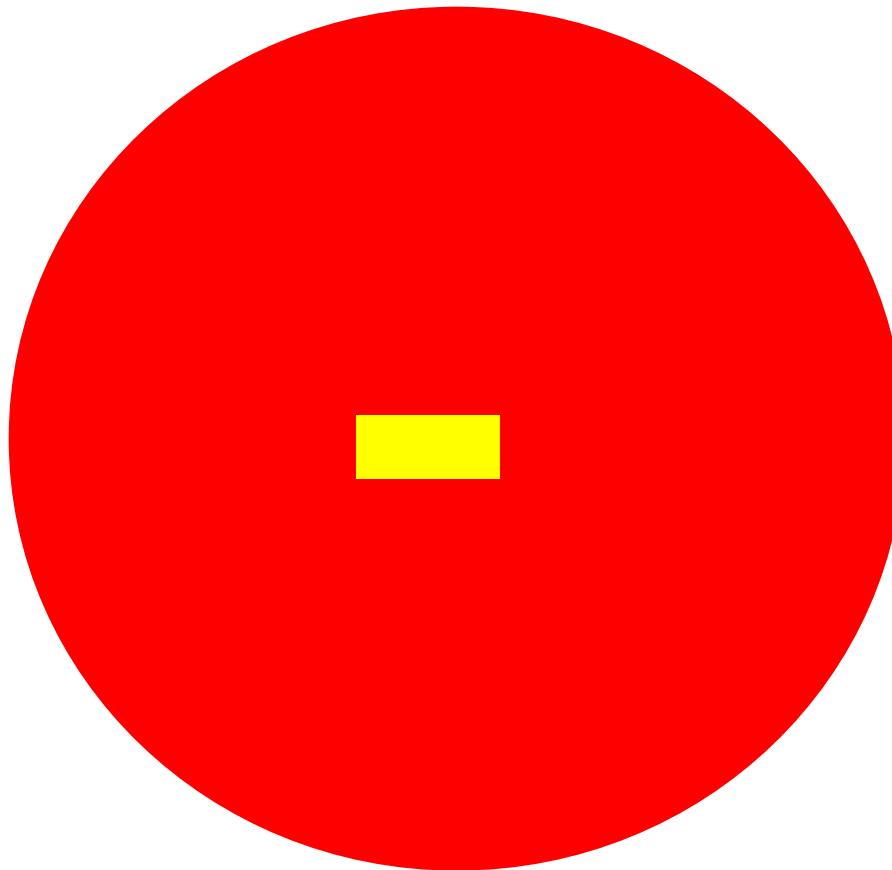


w/o



NEQ (kg)	B1	AASTP-1 Part IV*	
		FD(m)	QD(m)
50		15	N/A
100		19	N/A
500		32	64
1000		40	80
2000		50	101
4000		64	127

To narrow QD:S



new Criteria must be used

CONCLUSIONS

- The criteria for QD can be questioned
- QD:s have a long and well-established tradition and are easy to use but can not readily be used for Field Distances
- To reduce Field Distances higher blast levels must be accepted and measures taken to reduce effects from fragments and debris
- AASTP-5 strongly advocates the use of properly designed barriers.

Acknowledgement

- Thanks to AC/326 experts who have together created AASTP-5

THANK YOU

Bengt Vretblad

2010-07-13

